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SRTM Data Application for Extrapolation of Rating Curves (On the Example of the Iya River at the Tulun Gauge)

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Abstract. The manuscript discusses the method developed by the authors for restoring the cross-sectional area curve and extrapolate rating curves for the Iya River at the Tulun gauge, using the Shuttle Radar Topography Mission (SRTM) data. As part of the work, the systematic correction for the study area was determined to recalculate altitudes from a digital terranean model according to SRTM topographic data to the Baltic Height System. The river width data from SRTM-based information after systematic correction are in good agreement with the width from large-scale satellite images as well as with the field width measurements at appropriate levels. The paper presents the results of the extrapolation of the rating curve, using the Chezy equation approach, the Stevens-Velikanov technique and the stage-area and stage-velocity method, using the area curve and the average depth curve obtained on SRTM materials. For each research method used in the study, by comparing with the reference of rating curve, the values of the average probable deviation were calculated. As part of the study the extrapolated rating curve is presented as an analytical equation, and the approximation error is determined.

Keywords: the Iya River, SRTM data, stage, rating curve, extrapolation.

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Научная статья

Применение данных SRTM для экстраполяции кривых расходов (на примере поста р. Ия – г. Тулун)

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Аннотация. В ходе исследования авторами разработана методика применения данных радарной топографической съемки SRTM для восстановления кривой площадей и дальнейшей экстраполяции кривой расходов в створе гидрологического поста р. Ия – г. Тулун. Для пересчета отметок из цифровой модели рельефа по данным SRTM в Балтийскую систему определена систематическая поправка для изучаемой территории. Показано, что данные о ширине р. Ии по информации на основе SRTM после внесения систематической поправки хорошо соотносятся

с данными о ширине данного водотока по крупномасштабным космическим снимкам и с натурными измерениями этого параметра при соответствующих уровнях. В статье приводятся результаты экстраполяции кривой расходов по уравнению Шези, методу Стивенса – Великанова и по элементам расхода с привлечением кривой площадей и кривой средних глубин, полученных на основе материалов SRTM. Для каждого использованного в исследовании метода экстраполяции путем сопоставления с эталонной кривой расходов вычислены значения среднего вероятного отклонения. В рамках исследования экстраполированная кривая расходов аппроксимирована аналитическим выражением в форме параболы Глушкова, определена ошибка аппроксимации.

Ключевые слова: река Ия, кривые площадей, данные SRTM, кривые расходов, экстраполяция.

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Introduction

The purpose of the work is to study the possibility of using the radar topographic data to restore the cross-sectional area curve and extrapolate rating curves for the Iya River at the Tulun gauge.

Rating curves provide the hydrological information that can be used for water management and flood control. Measured water stages H can be converted into river discharges Q by means of a rating curve [Herschey, 1993; Abril, Knight, 2004; Rating curve modelling ... , 2000; Extrapolation of rating ... , 2010]. The rating curve at a gauge is a relation between stage and discharge $Q = f(H)$ that can be created experimentally from a set of direct stage-discharge observations for different periods [New method for ... , 2014; Development of River ... , 2019; Lima, Fernandes, Nascimento, 2019].

At extremely high-water levels it is not always possible to perform instrumental measurements of water flow. There is a need to extend or extrapolate the rating curve beyond the observed range, when the streamflow measurements are not available over the entire range of measured water stages [Jain, Singh, 2003], while it is important to have an area curve built up to a given extreme level value.

The object of study, the Iya River, flows down from the northeast slopes of the Eastern Sayan through the territory of the Irkutsk Region (Fig. 1). The watershed of the river up to the town of Tulun is 14 500 km². The water regime of the Iya River is characterized by spring-summer floods, high summer rainfall floods, and a low winter runoff. June–August are the most abundant months, accounting for almost 60 % of the annual river runoff [Modelling maximum discharge ... , 2020; Kalugin, 2021; Tsygankova, 2021].

There have been multiple catastrophic floods on the Iya River, including the floods in 1984, 2006 and 2019. In 2019 there was an increase in the water level, the biggest for the instrumental period of measurements of the Iya River at the Tulun gauge. It was up to 1389 cm which significantly exceeded the extreme level when the residential premises in this settlement to be flooded.



Fig. 1. The Iya River watershed at Tulun

Materials and Methods

In order to determine the morphometric cross-sectional characteristics (the river width, the area, the average depth, etc.) in the alignment of the Tulun stream gauge of the Iya River, the digital elevation model based on radar topographic void filled data at a resolution of 1 arc-second was used in the work. The Shuttle Radar Topography Mission (SRTM) has provided publicly available elevation surface data for approximately 80 % of the world's land surface area (from 60 ° N to 56 ° S) [Reuter, Nelson, Jarvis, 2007]. The SRTM altitude data is expressed in meters above EGM96 (The Earth Gravitational Model 1996) geoid.

The applicability of the SRTM data for determining the morphometric characteristics of water bodies was shown in a number of hydrological research [Drainage morphometry and..., 2013; Sutyryna, 2014; Her, Heatwole, Kang, 2015].

As part of the study, the following information was additionally involved: the morphometric data obtained during field discharge measurements for different years, daily information on stages, large-scale satellite images from the Google Earth service.

To test the proposed methodology, a set of historical field data on discharge measurement was selected. It makes possible to simulate unfavorable conditions for extrapolating the rating curve by more than 50 % of the stage amplitude.

In order to restore the cross-sectional area curve, the SRTM altitude data as well as the distances in the alignment of the Tulun stream gauge of the Iya River were used. To begin with, the width of the river B at various water level heights according to EGM96 was estimated on these data.

Based on large-scale satellite images from the Google Earth service the width of the river at the alignment of a given stream gauge for different dates was evaluated and compared with the simultaneous water levels given in the Baltic Height System.

According to the ratio of the Iya River width in the cross-section at the Tulun gauge with the water levels given in different height systems, a systematic correction was obtained for the given territory to recalculate the altitude data according to EGM96 to the Baltic Height System. It made possible to transfer the heights from one system to another and recalculate into the values of the stages H .

Results Discussion

The river width data from SRTM-based information after systematic correction are in good agreement with the width from large-scale satellite images and with field measurements of the width at the corresponding water levels (see fig. 2). It shows the reliability of the approach proposed by the authors for assessing morphometric characteristics based on the digital terrain model SRTM.

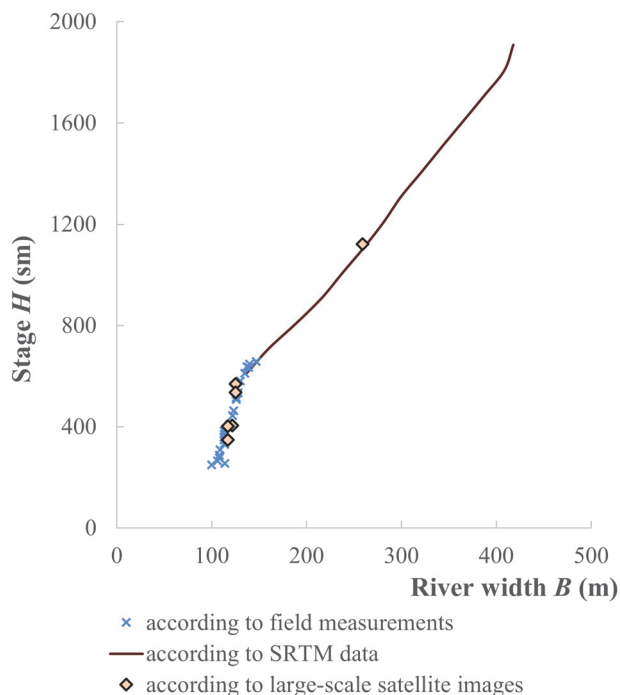


Fig. 2. Dependence of the River Iya width on the stage

Fig. 3 shows a good correspondence between the flood zone of the town of Tulun as of June 29, 2019, estimated by the authors, using SRTM data, and according to the data of the Sentinel-2 satellite. Based on the SRTM information, the flood zone was estimated using a static approximation, taking into account the level value on June 29, 2019, and the introduction of an estimated systematic correction. The good agreement between the areal and linear indicators obtained from the corrected SRTM data and information from other survey systems and field measurements shows the promise of using topographic radar data to assess morphometric parameters and reconstruct the curve of cross-sectional areas of the Iya River at the Tulun gauge.

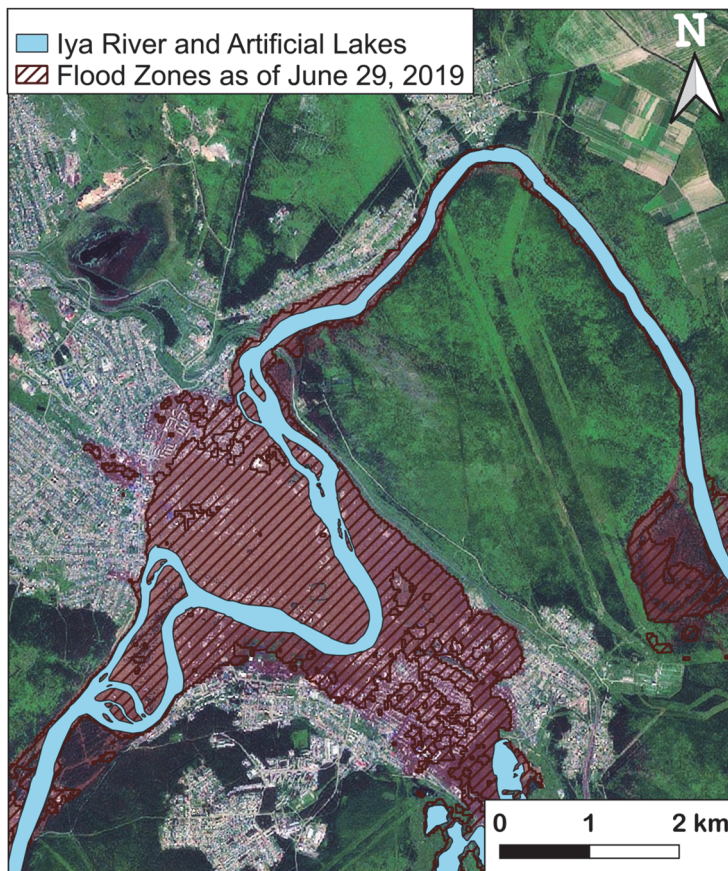


Fig. 3. The flood zone of the city of Tulun as of June 29, 2019, estimated using SRTM data by the authors in comparison with the Sentinel-2 image

Based on the data of the river width, obtained from the SRTM materials, at specific values of elevations/stages, the cross-sectional area of the Iya River at the Tulun gauge was calculated. The matter is that at altitudes up to 455.00 m in the Baltic Height System it is impossible to determine the width of this river accurately due to the specific scale and the lack of information about the underwater relief in

the digital terrain model according to the SRTM data. At the indicated altitude, the cross-sectional area was obtained from a section of the area curve according to field measurements. The subsequent increment of the cross-sectional area was determined based on the SRTM-derived river width data. It can be seen from the graph data (fig. 4A) that the area curves according to field measurements and the SRTM data are in good agreement.

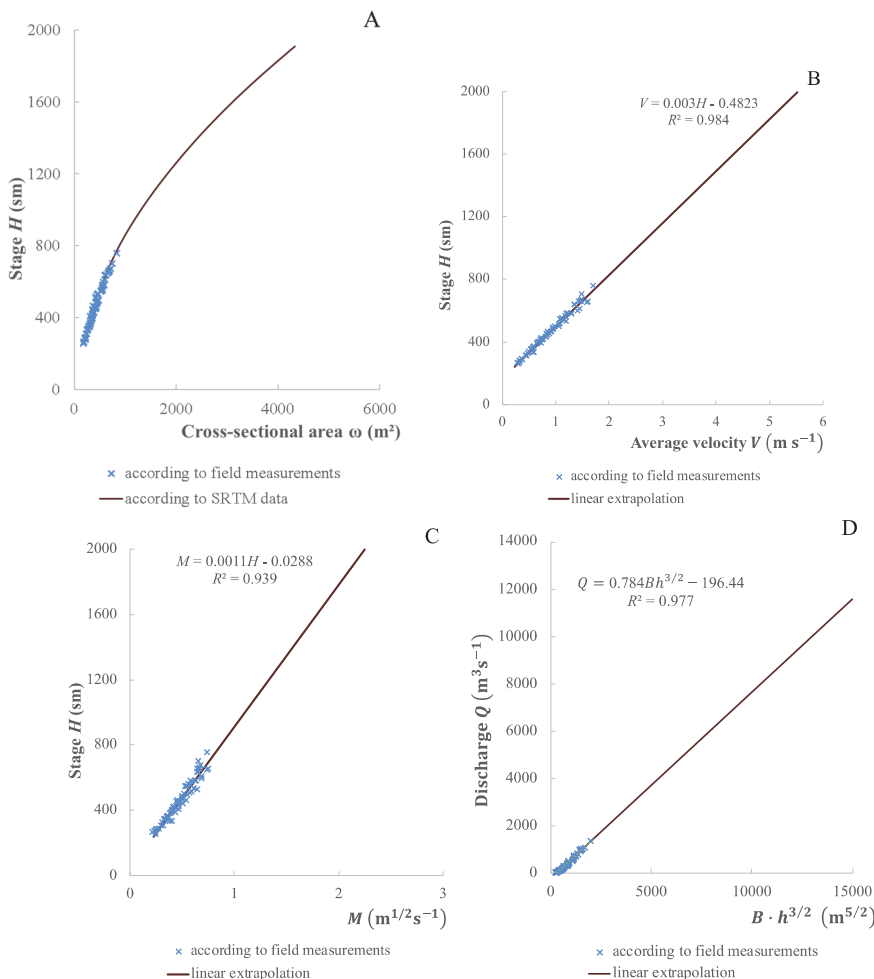


Fig. 4 The area curve reconstructed from the SRTM data (A), stage-velocity relation (B), stage-parameter M relation (C), dependence $Q = f(B \cdot h^{3/2})$ (D)

Meanwhile the method proposed by the authors demonstrates the relative ease of use and the ability to restore the cross-sectional area curve to the required extreme water level values, using a digital terrain model based on SRTM without additional field work. It shows the promise of the illustrated approach.

The area curve reconstructed from the SRTM data (see fig. 4A) is further used to high flow extrapolation of the rating curves in various ways: by the stage-area

and stage-velocity method, by the Stevens-Velikanov technique and by the Chezy equation approach.

The stage-area and stage-velocity extrapolation method is based on the observation that the stage-velocity relation has little curvature (see fig. 4B) and can be extended. The product of SRTM-derived cross-sectional area ω and average velocity V can be used to obtain values of discharge Q at a particular stage H .

The way to extrapolate the rating curve, using the parameter M is based on the application of the Chezy equation. The stream discharge Q at a particular stage H is defined as:

$$Q = \omega M \sqrt{h}, \quad (1)$$

where Q – water discharge ($\text{m}^3 \text{s}^{-1}$); ω – cross-sectional area, (m^2); $h = \omega/B$ – average depth (m); $M = V/\sqrt{h}$ ($\text{m}^{1/2} \text{s}^{-1}$); V – average flow velocity (m s^{-1}).

The M parameter is calculated from the measured streamflow. The relation $M=f(H)$ also has little curvature and can be extrapolated to the required values according to a certain linear equation (see fig. 4C). The average depth and cross-sectional area in the work was determined from the SRTM data.

According to the Stevens-Velikanov technique within the measured values of discharges, the dependence $Q = f(B \cdot h^{3/2})$ was determined and extrapolated by the linear equation (see fig. 4D). The value $B \cdot h^{3/2}$ was determined from morphometric data obtained from SRTM materials. Thus, knowing the SRTM-derived value $B \cdot h^{3/2}$ at a given stage H , it is possible, according to the obtained linear dependence $Q = f(B \cdot h^{3/2})$ to determine the amount of water discharge Q .

The obtained rating curves were verified by comparison with the rating curve used in the study as a reference, compiled according to long-term data in the Irkutsk UGMS (Irkutsk Department for Hydrometeorology and Environmental Monitoring) for the Iya River at the Tulun gauge. Fig. 5 shows the ratio of the extrapolated rating curves and the curve compiled in the Irkutsk UGMS. In the work, the values of the average probable deviation from the reference of rating curve of the extrapolated curves were determined. The curve obtained by extrapolation by the stage-area and stage-velocity method has a mean probable deviation value of 4.0 %. Extrapolated using the Stevens-Velikanov technique, the average probable deviation was 8.2 %, by the Chezy formula it was 7.3 %. Errors associated with high flow extrapolation of the rating curves can be caused by the occurrence of local backwater at extremely high-water levels of the Iya River near the Tulun stream gauge due to the limited capacity of the bridge openings [Estimates of Peak ... , 2020].

The rating curve reliability $Q = f(H)$ for the alignment of the Tulun stream gauge of the Iya River, obtained by the stage-area and stage-velocity extrapolation method, complies with more stringent requirements for rating curves created by gauged data.

To automate the streamflow calculation process, it is necessary to present the obtained rating curve in the form of an analytical expression. As an analytical expression of the stage-discharge rating curve in the framework of this research, the Glushkov parabola¹ was chosen.

¹ R 52.08.872-2018 *Operativnyy uchet stoka na vodotokakh. Metody obrabotki nablyudeniy za urovnyami i raskhodami vody* [R 52.08.872-2018. Operational metering of runoff on waterways. Methods for processing observations of water levels and discharges]. St. Petersburg, 2018, 107 p. (in Russian)

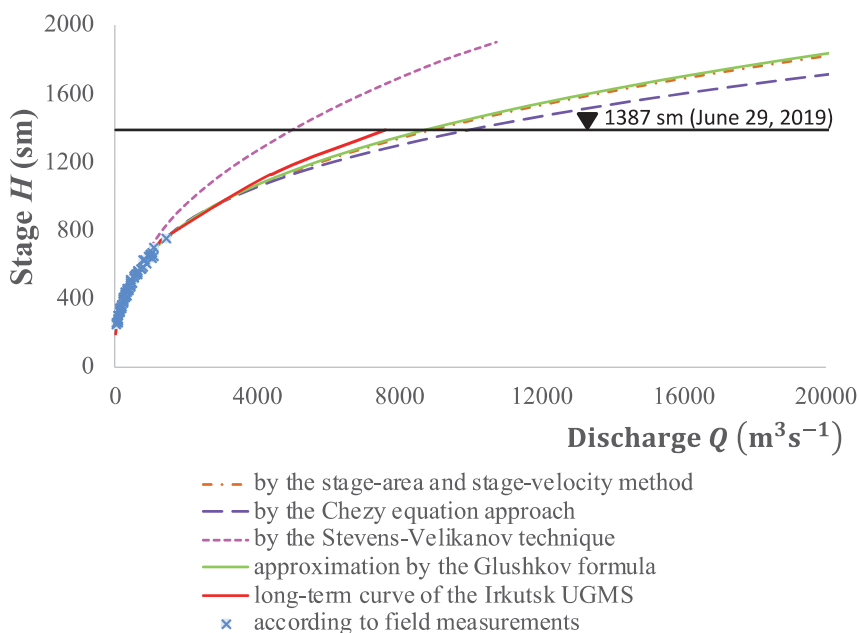


Fig.5 Ratio of extrapolated rating curves to long-term curve of the Irkutsk UGMS

It expresses the dependence of the flow rate on the level in the following form:

$$Q = a(H - H_0)^n, \quad (2)$$

where Q – water discharge ($\text{m}^3 \text{s}^{-1}$); H – observed water level (cm); H_0 – the stage at zero flow, where the water discharge in a given alignment is zero (cm); a and n – the parameters of the equation, determined in the framework of the research based on the rating curve, obtained by the stage-area and stage-velocity extrapolation method (see fig. 5).

As a rule, the stream gauge stage with zero value does not correspond to the level of zero discharge. The stage at zero flow can be determined from the results of survey work, but its determination in practice is difficult and requires the use of additional morphometric materials, which are often not available without additional field work. In this case, the stage at zero flow is found analytically by solving a system of equations written for three points: one located at the bottom of the rating curve ($Q_1; H_1$), the second is at the top ($Q_2; H_2$). The abscissa of the third point is found as $Q_3 = \sqrt{Q_1 Q_2}$ and along it with the rating curve is the ordinate H_3 . From these considerations, the stage at zero flow is found as:

$$H_0 = \frac{H_3^2 - H_1 H_2}{2H_3 - H_1 - H_2}. \quad (3)$$

The value of the zero-flow stage H_0 was obtained based on the formula (3). The parameters of the Glushkov parabola a and n are determined by the least square method.

The error of approximation by the Glushkov formula of the curve extrapolated by the stage-area and stage-velocity method is no more than 1.4 % (see fig. 5). On the section of the curve consecrated by the data of field measurements of discharge

rates, the resulting analytical expression is also verified by comparison with the reference rating curve compiled at the Irkutsk UGMS based on long-term gauged data. The average probable deviation from the reference curve is 3.4 %.

Conclusions

The study showed the prospects of restoring morphometric characteristics on the example of the cross-section of the Tulun stream gauge on the Iya River using SRTM radar topographic data according to the author's method. These linear and areal characteristics estimated from the radar data are in good agreement with data from other sources.

Using the area curve and the average depth curve obtained based on SRTM materials, the study extrapolated the rating curves of the Iya River at the Tulun gauge, according to the Chezy equation, the Stevens-Velikhanov technique and by the stage-area and stage-velocity method. The obtained rating curves were verified by comparison with the rating curve used in the study as a reference, compiled according to the long-term data in the Irkutsk UGMS for this site by calculating the values of the average probable deviation. The curve obtained by extrapolation by the stage-area and stage-velocity method has a probable deviation value of 4.0 %. Using other extrapolation methods, the error value turned out to be higher.

The results presented generally show the possibility of using SRTM survey data for the purposes of reconstructing cross-sectional area curves and extrapolating rating curves to the required levels.

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